

Biomimetic Design of Biodegradable Polymer Films for Sustainable Food Packaging: Integrating Indigenous Material Wisdom with Modern Chemistry

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Abstract

The increasing environmental burden from petroleum-based plastics necessitates the exploration of sustainable alternatives inspired by nature and traditional material practices. This study presents the development of biodegradable food packaging films derived from indigenous biopolymers such as sodium alginate, chitosan, and poly (γ -glutamic acid), integrated with natural additives including lignin nanoparticles and jackfruit seed extract. Guided by the principles of biomimicry and indigenous ecological wisdom, the formulation aims to emulate the functional resilience and biodegradability of natural plant cuticles. Physicochemical, mechanical, and barrier properties of the films were characterised to assess their potential as eco-friendly packaging materials. The findings highlight the role of traditional knowledge systems in guiding sustainable material innovation and promoting circular economy practices. This work bridges indigenous wisdom and modern polymer chemistry, contributing to the advancement of green technologies aligned with the United Nations Sustainable Development Goals (SDGs 12 and 13).

Keywords: Biomimicry, Biodegradable polymers, Indigenous knowledge, Sustainable packaging, Chitosan, γ -PGA, Circular economy.

1. Introduction

The rapid growth of synthetic plastic waste has become a significant global issue, greatly contributing to environmental pollution, ecological toxicity, and greenhouse gas emissions (1). Conventional packaging films made from polyethene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethene terephthalate (PET) possess excellent mechanical stability and barrier properties but are not biodegradable, leading to their buildup in landfills, land ecosystems, and oceans (2,3). The shift toward sustainable packaging materials has thus become an urgent scientific and socio-economic priority aligned with the United Nations Sustainable Development Goals (SDGs), especially SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) (4).

Biodegradable polymers derived from natural, renewable feedstocks offer a promising alternative to petroleum-based plastics. Their capacity to decompose into environmentally benign products and compatibility with circular economy strategies make them attractive candidates for next-generation packaging materials (5–7). However, widespread adoption requires overcoming challenges associated with their mechanical performance, water sensitivity, film-forming ability, processability, and cost-effectiveness (8). To address these limitations, modern polymer chemistry increasingly turns toward biomimicry — the design and engineering of materials inspired by natural systems — and indigenous material knowledge, which embodies centuries of empirical understanding of natural resources and sustainable practices.

This review synthesizes advances in biomimetic design strategies involving biopolymers such as sodium alginate, chitosan, and poly (γ -glutamic acid) (γ -PGA), combined with indigenous-derived additives like lignin nanoparticles and jackfruit seed extract. These materials emulate the hierarchical organization, barrier efficiency, and adaptive resilience found in natural plant cuticles and biological protective layers (9). By integrating ecological wisdom with modern chemical engineering, biodegradable films can be rationally designed to enhance their mechanical, physicochemical, barrier, and antimicrobial performance, making them viable for food packaging applications (10, 11).

2. Nature-Inspired Design in Packaging Materials

Biomimicry is a multidisciplinary approach that leverages principles observed in natural biological structures—such as self-healing, hierarchical assembly, water repellence, and selective permeability—to inform the design of advanced synthetic and bio-based materials (12). The plant cuticle, insect wings, and microbial biofilms have attracted particular attention because their naturally evolved structures achieve a unique balance of flexibility, strength, and barrier performance (13).

2.1. Plant Cuticle as a Model Protective Layer

The plant cuticle is a composite structure composed of waxes, polysaccharides, and cutin, forming a hydrophobic yet selective barrier that regulates moisture, gas transport, and pathogen resistance (14). Similar to packaging films, the cuticle must prevent water loss, provide mechanical stability, and protect against microbial attack. Its multilayered architecture—featuring crystalline wax domains embedded within a polymer matrix—serves as an exemplary model for engineered biofilms (15).

Biomimetic biopolymer films designed with hydrophilic polysaccharides such as alginate or γ -PGA often incorporate hydrophobic additives (e.g., essential oils, lignin, or waxes) to mimic this amphiphilic nature and improve water resistance (16).

2.2. Hierarchical Structure and Natural Polymer Assembly

Many natural biopolymers, including cellulose, chitin, collagen, and gelatin, exhibit hierarchical arrangements of fibers, crystallites, and cross-links that provide exceptional mechanical performance (17). This structural organisation inspires the controlled assembly of synthetic composite films where nanoscale fillers (e.g., lignin nanoparticles) reinforce polymer matrices, resulting in improved tensile strength and thermal stability (18).

2.3. Bioinspired Barrier Functions

Selective barrier properties in natural systems—such as stomatal regulation, suberin lamellae, or insect cuticle permeability—guide the optimization of gas and vapor transmission in biodegradable packaging films (19). The engineering of cross-linked networks in alginate and chitosan films further allows modulation of oxygen permeability and moisture sensitivity (20).

These biomimetic strategies form the foundation for developing multifunctional films that address the limitations of single-component biopolymers.

3. Indigenous Material Knowledge and Ecological Wisdom

Indigenous knowledge systems (IKS) have contributed substantially to sustainable material innovations long before modern polymer science existed. Many natural resources used in traditional preservation, storage, and wrapping techniques bear a striking resemblance to the biomaterials studied today (21).

3.1. Traditional Food-Storage Practices as Material Models

Communities across Asia, Africa, and South America historically used plant leaves (banana, teak, sal, areca) for wrapping food due to their natural barrier properties, antimicrobial activity, and biodegradability (22). The layered cuticular structure of leaves inspired the concept of natural composite films—an approach reflected in modern multilayer biopolymer packaging (23).

Similarly, indigenous fermentation vessels made of natural gums, resins, and polysaccharides demonstrate the stabilising role of natural polymers in moisture regulation and microbial control (24).

3.2. Indigenous Polysaccharide-Based Adhesives and Coatings

Traditional adhesives made from tamarind seed polysaccharides, gum arabic, and plant mucilage share compositional similarities with sodium alginate and chitosan solutions used in contemporary film formation (25). These adhesives exhibit intrinsic viscosity, film-forming capability, and adhesive strength comparable to engineered biopolymers (26).

Understanding these traditional formulations offers insights into optimizing modern film parameters such as viscosity, drying behaviour, and cross-linking density.

3.3. Natural Antimicrobials and Preservatives

Indigenous communities widely employed plant extracts (turmeric, neem, jackfruit seed, clove) as antimicrobial agents for food protection (27). Phytochemicals such as phenolics,

flavonoids, and alkaloids present in these extracts function as natural preservatives with documented antioxidant and antimicrobial activities (28). When incorporated into biopolymer matrices, these compounds enhance shelf life and food safety by inhibiting microbial growth and oxidative degradation (29).

The integration of jackfruit seed extract into polymer films exemplifies the synergy between traditional ethnobotanical knowledge and modern biomaterial engineering (30).

4. Advances in Biodegradable Polymers for Packaging

Biopolymers derived from renewable resources have emerged as essential components for sustainable packaging solutions. Among the most promising materials are sodium alginate, chitosan, and poly (γ -glutamic acid) (γ -PGA), each offering unique physicochemical properties relevant to film formation and food preservation.

4.1. Sodium Alginate: Chemistry, and Functional Properties

Sodium alginate is a naturally occurring anionic polysaccharide obtained primarily from brown seaweeds (31). It consists of β -D-mannuronic acid (M units) and α -L-guluronic acid (G units) arranged in homopolymeric (MM, GG) or heteropolymeric (MG) blocks (32). The ratio and distribution of these units significantly influence the polymer's gel-forming ability and mechanical properties.

4.1.1. Ionotropic Gelation and Cross-Linking

Alginate exhibits ionotropic gelation in the presence of divalent cations such as Ca^{2+} , which bind preferentially to G-block sequences to form “egg-box” junction zones (33). This cross-linking yields mechanically strong, water-insoluble networks, crucial for improving the water barrier properties of films (34). The incorporation of CaCl_2 or other cross-linking salts during film fabrication results in enhanced tensile strength and reduced solubility (35).

4.1.2. Film-Forming Ability

Due to its hydrophilic nature and chain flexibility, alginate forms transparent, smooth films when cast from aqueous solution (36). However, its high moisture sensitivity necessitates

reinforcement with hydrophobic agents or nanoparticles to achieve packaging-grade water resistance (37).

4.2. Chitosan: Biocompatible Polycation for Active Packaging

Chitosan is derived from the deacetylation of chitin, the second most abundant natural polymer (38). Its polycationic nature, resulting from protonated amino groups at acidic pH, imparts antimicrobial activity and the ability to form electrostatic complexes with anionic compounds (39).

4.2.1. Antimicrobial Mechanism

Chitosan disrupts microbial membranes through electrostatic interactions, chelation of essential nutrients, and interference with DNA/RNA synthesis (40). This intrinsic activity positions chitosan as a cornerstone in active packaging designed to prolong shelf life (41).

4.2.2. Mechanical Properties and Blending Strategies

Chitosan films are strong, flexible, and oxygen-impermeable, but they remain sensitive to water (42). Blending with cross-linkers, plasticizers (e.g., glycerol), or fillers (e.g., lignin nanoparticles) enhances their durability (43).

4.3. Poly (γ -Glutamic Acid): Emerging Biopolymer with High Functional Potential

Poly (γ -glutamic acid) (γ -PGA) is a microbial polymer produced mainly by *Bacillus* species during fermentation (44). It consists of glutamic acid monomers linked via γ -amide bonds, giving it exceptional water solubility, biodegradability, and metal-binding capabilities (45).

4.3.1. Role in Film Formation

Thanks to its high viscosity and polyanionic character, γ -PGA forms cohesive films compatible with other polysaccharides and natural extracts (46). Its capacity for hydrogen bonding and electrostatic interactions enables the creation of hybrid films with improved tensile and barrier properties (47).

5. Functional Additives in Biomimetic Biopolymer Films

Enhancing the performance of biodegradable films often requires incorporating additives that impart strength, antimicrobial action, UV protection, or improved barrier properties. Two such promising additives—lignin nanoparticles and jackfruit seed extract—are derived from biological and indigenous sources, making them ideal for sustainable and eco-centric packaging solutions.

5.1. Lignin Nanoparticles (LNPs): A Bioinspired Structural Reinforcer

Lignin is a complex aromatic biopolymer that contributes to the rigidity and hydrophobicity of plant cell walls (48). Its unique structure—rich in phenolic units—provides antioxidant activity and UV-blocking capability, making it highly relevant for packaging applications (49).

5.1.1. Advantages of Nano structuring Lignin

Converting lignin into nanoparticles significantly enhances its surface area, dispersibility, and reinforcing effectiveness in polymer matrices (50). Lignin nanoparticles (LNPs) can be synthesized via solvent exchange, ultrasonication, or acid precipitation methods (51).

Key advantages:

- Improved mechanical reinforcement via hydrogen bonding and π – π interactions (52)
- Increased hydrophobicity, reducing water vapor permeability (53)
- Strong UV-light absorption, protecting packaged food from degradation (54)
- Phenolic radicals contribute natural antioxidant properties (55)

5.1.2. Interactions with Alginate, Chitosan, and γ -PGA

LNPs interact differently with each polymer:

- **Alginate:** Hydrogen bonding between –OH/COOH groups and LNP phenolics increases cross-link density (56).
- **Chitosan:** Electrostatic and covalent interactions improve modulus and reduce brittleness (57).
- **γ -PGA:** Strong hydrogen bonding results in enhanced film stiffness and decreased solubility (58).

Thus, LNPs serve as multifunctional reinforcement agents that support the biomimetic design goals of structural robustness and environmental resistance.

5.2. Jackfruit Seed Extract (JSE): Indigenous Antimicrobial and Antioxidant Agent

Jackfruit seed extract, rich in phenolic compounds, flavonoids, tannins, and alkaloids, is traditionally used in many Indian communities for food preservation and medicinal purposes (59). Its antimicrobial and antioxidant properties make it an effective functional additive in biodegradable films (60).

5.2.1. Phytochemical Profile

Major constituents include:

- Phenolics (gallic acid, catechin)
- Flavonoids (quercetin derivatives)
- Tannins
- Lectins and proteins
- Antioxidant amino acids (61)

These compounds provide radical-scavenging ability, antimicrobial activity, and potential for cross-linking with polymer matrices (62).

5.2.2. Mechanism of Antimicrobial Action

JSE inhibits microbial growth through:

- Membrane disruption via phenolic compounds (63)
- Metal chelation affecting microbial enzymatic pathways (64)
- Oxidative stress induction in bacterial cells (65)

When combined with chitosan or alginate, synergistic antimicrobial effects are often observed (66), enhancing the film's role as an active packaging material.

5.3. Role of Plasticizers: Glycerol as a Key Component

Plasticizers reduce intermolecular forces in polymer matrices, increasing flexibility and preventing brittleness during film formation (67). Among available plasticizers—sorbitol, glycerol, polyethylene glycol—glycerol is most widely used due to its low cost, compatibility with hydrophilic polymers, and non-toxicity (68).

5.3.1. Effect on Mechanical Properties

Glycerol increases elongation at break by enhancing polymer chain mobility but may reduce tensile strength if used in excess (69). Optimal concentrations typically range from 20–35% w/w of polymer solids (70).

5.3.2. Influence on Water Sensitivity

Although glycerol improves flexibility, its hygroscopic nature increases water vapor permeability (71). Therefore, glycerol-containing films often require hydrophobic additives (e.g., LNPs) or cross-linking to restore barrier properties (72).

6. Film Preparation Strategies

To design biomimetic biodegradable films, the chosen method of preparation significantly influences film morphology, crystallinity, mechanical performance, and barrier functionality. The three dominant fabrication techniques are solvent casting, extrusion, and electrospinning.

6.1. Solvent Casting Technique

Solvent casting remains the most common method for preparing biopolymer films due to its simplicity and suitability for hydrophilic polymers like alginate and γ -PGA (73).

6.1.1. Procedure Overview

Steps include:

1. Dissolving the polymer in water or dilute acid (for chitosan) (74).
2. Adding plasticizers (glycerol) and functional additives (LNPs, JSE) (75).
3. Degassing to remove air bubbles.
4. Pouring onto a flat surface or petri dish.
5. Controlled drying at ambient or reduced temperatures (76).

6.1.2. Advantages and Limitations

Advantages:

- Low-cost, simple, suitable for lab-scale production.
- Provides uniform thickness.
- Enables incorporation of sensitive bioactive compounds (77).

Limitations:

- Slow drying time.
- Limited scalability compared to industrial extrusion (78).

6.2. Extrusion Techniques

Extrusion involves melting or softening polymers to form continuous films, widely used in industrial packaging (79). For biodegradable polymers, extrusion is challenging due to thermal sensitivity, but modifications allow composite formulations to be extruded successfully (80).

6.2.1. Compatibility of Biopolymers

Alginate and chitosan typically cannot be melted directly but can be blended with thermoplastic starch or polyesters (PLA, PHA) to enable extrusion (81). γ -PGA, being thermally unstable, is also usually combined with compatible polymers (82).

6.2.2. Advantages

- Industry-ready scalable process
- Produces strong, oriented films
- Allows multilayer composite structures (83)

6.3. Electrospinning of Biopolymer Nanofibers

Electrospinning generates ultrafine fibers (50–500 nm), creating films with high surface area and tuneable porosity (84).

6.3.1. Relevance to Biomimetic Design

Electro spun films mimic natural extracellular matrices and spider silk structures, offering enhanced mechanical and barrier characteristics (85).

6.3.2. Application

Used for antimicrobial coatings, oxygen scavenging layers, and active packaging components (86).

7. Characterization of Biodegradable Packaging Films

Evaluating the physicochemical, mechanical, barrier, thermal, and antimicrobial properties of the biopolymer films is essential to ensure their effectiveness for packaging applications.

7.1. Mechanical Properties

Mechanical tests determine tensile strength (TS), elongation at break (EAB), and Young's modulus.

7.1.1. Influence of Polymer Composition

- Alginate films cross-linked with Ca^{2+} exhibit high TS due to formation of rigid junction zones (87).
- Chitosan contributes to film toughness via intermolecular hydrogen bonding (88).
- γ -PGA improves flexibility because of its polyanionic chain architecture (89).

7.1.2. Effects of Additives

- LNPs increase TS via nanofiller reinforcement (90).
- Glycerol increases EAB but may reduce TS at higher levels (91).
- JSE can act as a secondary cross-linker, altering film stiffness (92).

7.2. Water Vapor Permeability (WVP)

Low WVP is essential to limit moisture transfer between food and environment.

7.2.1. Determinants of WVP

- Hydrophilicity of the polymer (93)
- Cross-link density (94)
- Incorporation of hydrophobic fillers like LNPs (95)

Alginate and chitosan films typically exhibit high WVP; however, LNP incorporation and Ca^{2+} cross-linking significantly reduce moisture permeability (96).

7.3. Oxygen Transmission Rate (OTR)

Biopolymer films generally exhibit excellent oxygen barrier properties due to their dense hydrogen-bonded networks (97). Chitosan is especially effective as an oxygen barrier (98).

Additives such as LNPs further decrease OTR by increasing path tortuosity (99).

7.4. Optical Properties

Transparency and UV-shielding are crucial.

- Polysaccharide films are typically transparent (100).
- LNPs impart UV-blocking ability due to aromatic chromophores (101).
- JSE may increase yellowness but enhances antioxidant protection (102).

7.5. Thermal Stability

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) assess decomposition profiles and thermal transitions.

- γ -PGA-based films exhibit improved stability due to strong hydrogen bonding (103).
- LNPs act as thermal reinforcers, delaying degradation onset (104).

7.6. Antimicrobial and Antioxidant Activity

7.6.1. Antimicrobial Activity

Chitosan and JSE provide broad-spectrum inhibition against:

- *Escherichia coli*
- *Staphylococcus aureus*

- *Aspergillus niger* (105)

LNPs also contribute mild antimicrobial action through phenolic groups (106).

7.6.2. Antioxidant Activity

Assessed by DPPH or ABTS radical assays, antioxidant activity is significantly enhanced by incorporation of JSE and LNPs (107,108).

8. Applications in Food Packaging

Biodegradable polymer films made from sodium alginate, chitosan, poly (γ -glutamic acid), pullulan, galactomannan, lignin nanoparticles, and jackfruit seed extract represent a versatile class of materials well-suited for a variety of food packaging applications. Their performance is a result of synergistic interactions among polysaccharides, plasticizers, polyphenolic bioactives, and nanofillers, giving rise to films with excellent transparency, tunable mechanical strength, enhanced barrier properties, and substantial bioactivity (109).

8.1 Packaging of Fresh Fruits and Vegetables

Fresh fruits and vegetables undergo rapid deterioration due to moisture loss, respiration, and enzymatic oxidation. Polysaccharide-based films, particularly alginate and pullulan formulations, are effective in reducing gas exchange, controlling transpiration, and maintaining firmness. The incorporation of jackfruit seed extract increases antioxidant activity and reduces enzymatic browning, making these films suitable for apples, pears, berries, mangoes, and cut fruits (110,111). Lignin nanoparticles contribute UV-blocking properties, protecting light-sensitive produce and delaying photosensitized degradation (112).

8.2 Meat, Poultry, and Seafood

Oxidation of lipids and pigments is a major challenge in meat packaging. Active films containing jackfruit seed polyphenols and lignin nanoparticles suppress lipid peroxidation and microbial growth due to strong radical-scavenging and antimicrobial effects (113). Chitosan-based layers enhance bacteriostatic performance against *E. coli*, *Salmonella*, and *Listeria monocytogenes* (114). These films can be used as primary wraps, inner liners, and interleaving sheets for steaks, poultry parts, fish fillets, and marinated seafood (115).

8.3 Bakery, Snack Foods, and Confectionery

Pullulan-rich films exhibit outstanding oxygen barrier properties, essential for protecting bakery and snack foods from oxidative rancidity (116). Galactomannan contributes to matrix densification, lowering water vapor permeability and improving crispness retention. Such films are suitable for packaging cookies, crackers, wafers, dried fruits, and candies. Natural antioxidants incorporated into the films delay fat oxidation in high-fat snacks (117).

8.4 Minimally Processed and Ready-to-Eat (RTE) Foods

Biodegradable films with antimicrobial and antioxidant properties are well-suited for RTE items such as salads, cheese slices, tortillas, and sandwiches (118). Their edibility and non-toxicity allow for direct wrapping applications. Alginate–pullulan blends form flexible, transparent films that can serve as edible wraps or secondary packaging (119). Composite films may also function as carriers for flavorings, probiotics, or nutraceuticals in functional food packaging (120).

9. Environmental Performance

Evaluating the environmental sustainability of polymer films requires consideration of feedstock origin, carbon emissions, biodegradability, and end-of-life impacts. Films derived from alginate, pullulan, galactomannan, chitosan, γ -PGA, lignin, and jackfruit seed extract demonstrate excellent environmental performance compared to conventional plastics (121).

9.1 Use of Renewable and Abundant Feedstocks

Most biopolymers used here are derived from renewable sources: seaweed (alginate), microbial fermentation (pullulan, γ -PGA), legumes (galactomannan), crustacean shells (chitosan), and agro-industrial waste streams (jackfruit seeds, lignin). Utilizing lignin and jackfruit seed waste adds circularity by valorising biomass that is typically discarded (122,123).

9.2 Carbon Footprint and Energy Consumption

The carbon footprint of biopolymer film production is generally lower than that of petroleum-based plastics due to the reduced emissions involved in extraction and processing (124).

Solvent casting and aqueous processing demand minimal thermal energy. The incorporation of low-cost fillers such as lignin nanoparticles reduces polymer consumption and promotes energy-efficient material optimization (125).

9.3 Lower Ecotoxicity and Reduced Microplastic Pollution

Unlike polyethylene or polypropylene, biodegradable films do not accumulate in ecosystems. Their degradation does not yield persistent microplastics, and their breakdown products—oligosaccharides, simple sugars, organic acids—are environmentally benign (126). Lignin nanoparticles exhibit low cytotoxicity and degrade naturally through oxidative and microbial pathways (127).

10. Life Cycle and Biodegradation

Biodegradability is central to evaluating the sustainability of biopolymer films. Life cycle analysis (LCA) integrates production, use, and end-of-life phases to provide a holistic perspective.

10.1 Biodegradation in Soil and Compost

Biopolymer films typically degrade through hydrolysis, enzymatic cleavage, and microbial assimilation. Alginate, chitosan, and galactomannan films degrade in soil within 30–60 days under warm, moist conditions (128). Compost conditions (high microbial load, 50–60°C) accelerate biodegradation and mineralization, with complete disintegration observed within 2–8 weeks depending on film composition and thickness (129).

10.2 Biodegradation in Aquatic Systems

Polysaccharide-based films degrade significantly faster in freshwater due to higher solubility, aggressive microbial action, and physical disintegration (130). The incorporation of lignin nanoparticles slows excessive swelling but still allows eventual biodegradation. Chitosan films exhibit strong antimicrobial activity initially, but degrade over time via chitosanase-producing microbes (131).

10.3 Life Cycle Assessment

LCA studies consistently report lower environmental burdens for biodegradable films than petroleum-based plastics:

- 40–70% reduction in CO₂ emissions
- Lower fossil energy demands
- Reduced toxic chemical release
- High end-of-life biodegradability

The extraction of certain polymers (e.g., pullulan) remains energy-intensive (132). Future improvements in fermentation efficiency, solvent recovery, and green extraction will further reduce environmental impact (133).

11. Limitations and Future Directions

11.1 Current Limitations

Despite clear advantages, several constraints hinder large-scale commercialization:

1. Moisture sensitivity

Polysaccharide films absorb water readily, compromising mechanical and barrier performance in humid environments (134).

2. Lower mechanical strength

Compared with LDPE or PET, biodegradable films exhibit lower tensile strength unless reinforced with nanomaterials (135).

3. High cost of some components

Pullulan and γ -PGA are expensive to produce at industrial scale; fermentation processes require optimization (136).

4. Processing and scalability barriers

Solvent casting is slow and energy-intensive for industrial production. Extrusion and blow-moulding methods require improvements (137).

5. Variable shelf stability

High hydrophilicity reduces long-term storage stability of films (138).

6. Regulatory and market acceptance issues

Adoption is limited by regulatory hesitations, cost–benefit uncertainties, and consumer perception (139).

11.2 Future Research Directions

Enhancing film performance and scalability requires innovative approaches:

1. Chemical and physical cross linking

To reduce water sensitivity and improve tensile properties (140).

2. Advanced nanocomposites

Incorporation of cellulose nanofibers, nanoclays, or hybrid nanofillers with lignin nanoparticles for synergistic reinforcement (141).

3. Green extraction technologies

Use of ultrasound, microwave, or deep eutectic solvents for isolating jackfruit seed extract and lignin (142).

4. Bioactive and intelligent packaging

Integration of natural indicators for pH, freshness, spoilage detection, or controlled release of antioxidants/antimicrobials (143).

5. Edible and nutraceutical packaging

Films that carry probiotics, vitamins, or bioactives to improve consumer health (144).

6. Industrial-scale extrusion

Development of melt-processable blends compatible with commercial film production (145).

With research advancements and technological innovation, these films can become competitive substitutes for petrochemical plastics.

12. Conclusion

The integration of biomimetic design principles with indigenous material wisdom offers a transformative approach to sustainable food packaging. Composite films based on sodium alginate, chitosan, pullulan, galactomannan, γ -PGA, lignin nanoparticles, and jackfruit seed extract demonstrate remarkable potential as eco-friendly packaging materials. Their biodegradability, bioactivity, tuneable mechanical strength, and excellent barrier properties align with global goals for reducing plastic waste and promoting circular economy practices.

Although challenges related to cost, scalability, and water sensitivity persist, ongoing advances in polymer chemistry, nanotechnology, crosslinking, and green extraction methods provide clear pathways for improvement. These biodegradable films represent a promising step toward replacing conventional plastics in food packaging and supporting sustainable development objectives.

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